THE MOLECULAR ISM OF LOW SURFACE BRIGHTNESS SPIRAL GALAXIES

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Abstract I summarize some results from the recent CO survey of late-type, low surface brightness (LSB) spiral galaxies by Matthews et al. (2005). We have now detected CO emission from six late-type, LSB spirals, demonstrating that despite their typical low metallicities and low mean gas surface densities, some LSB galaxies contain a molecular medium that is traced by CO. We find that the CO-detected LSB spirals adhere to the same $M_{\rm H_2}$-FIR correlation as brighter galaxies. We also find a significant drop-off in the detectability of CO among low-to-intermediate surface brightness galaxies with $V_{\rm rot} \lesssim$90km s^{-1}, pointing toward fundamental changes in the physical conditions of the ISM with decreasing disk mass.

1. Background

Low surface brightness (LSB) spiral galaxies are defined as having central disk surface brightnesses $\mu(0)_B \gtrsim$23 mag arcsec^{-2}, indicating low stellar surface densities. However, despite their faint optical appearances, the majority of LSB spirals show evidence for ongoing star formation, including blue colors, Hα emission and/or resolved populations of young stars (e.g., Schombert et al. 1992; Gallagher & Matthews 2002). Signatures of star formation are frequently coupled with large atomic gas fractions ($M_{\rm HI}/L_B$ ∼1), underscoring that LSB spirals are not the faded remnants of brighter galaxies. In a number of cases, evidence is also seen for stellar populations spanning a wide range of ages (e.g., van den Hoek et al. 2000), implying that LSB spirals have been forming stars for a significant fraction of a Hubble time—but with low efficiency.

Lingering questions regarding the evolutionary history of LSB spirals are *why* their star formation has remained suppressed, and what physical processes regulate the type of low-level star formation that is observed in these systems. Given that LSB spirals comprise a significant fraction (∼50%) of the local disk galaxy population (e.g., Minchin et al. 2004), answers to these questions

are crucial for our overall understanding of the star formation history of the universe. In addition, they are relevant to understanding star formation in other low-density and/or low-metallicity environments, including protogalaxies, the outskirts of giant galaxies, and damped Lyα absorption systems.

2. Studies of the ISM of LSB Spirals

2.1 Past Results

Key to understanding the process of star formation in LSB spirals is an improved knowledge of the composition and structure of their interstellar medium (ISM). To date, most of our knowledge of the ISM in LSB spirals comes from studies of their H I gas, which appears to be by far the dominant component of their ISM ($\gtrsim$95% by mass). H I studies have shown that while H I is typically present throughout the stellar disk of LSB spirals, H I surface densities often fall below the critical threshold for instability-driven star formation throughout most or all of their disks (e.g., van der Hulst et al. 1993; de Blok et al. 1996).

In a broad sense, the low H I densities of LSB spirals seem to account naturally for their inefficient star formation. However, this explanation is not entirely satisfactory for several reasons. First, important ISM parameters including the gas scale height, volume density, and turbulent velocity remain poorly constrained. Secondly, we know some star formation is occurring in LSB spirals in spite of subcritical H I surface densities. Furthermore, it is ultimately from the molecular, not the atomic gas that stars form. It is clear that a more comprehensive picture of star formation in LSB spirals requires a more complete knowledge of their multi-phase ISM.

Unfortunately, direct searches for molecular gas in LSB spirals have proved to be challenging. Indeed, initial searches for CO emission from late-type, LSB spirals failed to yield any detections (Schombert et al. 1990; de Blok & van der Hulst 1998), leading to the suggestions that the metallicities of typical LSB spiral may be too low for the formation of CO molecules or efficient cooling of the gas, that the interstellar pressures may be insufficient to support molecular clouds, or that star formation may occur directly from the atomic medium (Schombert et al. 1990; Bothun et al. 1997; Mihos et al. 1999).

2.2 New Results from Deep CO Surveys

To partially circumvent the challenges of detecting CO emission from LSB spirals, my collaborators and I began surveying examples of LSB spirals viewed *edge-on*, using observations 2-3 times deeper than previous studies. Our targets comprised extreme late-type (Scd-Sm) LSB spirals with redshifts $V_r \leq$2000 km s^{-1}. Two advantages of our approach are: (1) the column depth of the molecular gas is enhanced for an edge-on geometry; and (2) an edge-on view-

ing angle allows complementary studies of the vertical structure of various ISM and stellar components of the galaxies at other wavelengths.

In a pilot survey with the NRAO 12-m telescope, we detected for the first time ^{12}CO(1-0) emission from three late-type, LSB spiral galaxies (Matthews & Gao 2001). More recently, we followed up with a more extensive survey of 15 LSB spirals in both the ^{12}CO(1-0) and ^{12}CO(2-1) lines using the IRAM 30-m telescope (Matthews et al. 2005; hereafter M05). In this latter survey, we detected CO emission from the nuclear regions of four LSB spirals, one of which was previously detected by Matthews & Gao (2001; Fig. 1). For the galaxies detected in these two surveys, we estimate the molecular hydrogen content of the nuclear regions (central 1-3 kpc) to be $M_{\rm H_2} \approx (0.3-2)\times10^7~M_\odot$, assuming a standard Galactic CO-to-H_2 conversion factor. While the conversion of CO flux to H_2 mass in low-density, low-metallicity galaxies can be rather uncertain, *these observations have clearly established that at least some bulgeless, late-type, LSB spirals contain modest amounts of molecular gas in their nuclear regions, and that CO traces at least some fraction of this gas.* In addition, our results establish that a bulge is not a prerequisite for the presence of molecular gas at the centers of low-density LSB galaxies. Therefore our surveys extend the realm of CO-detected LSB spirals from the giant, bulge-dominated LSB systems detected by O'Neil et al. (2000,2003) and O'Neil & Schinnerer (2004) to the more common, low-mass, pure-disk LSB systems.

While the samples of late-type, LSB spirals surveyed in CO are still small, already some interesting trends are emerging. Here I briefly describe two of our key findings. For further results and discussion, I refer the reader to M05.

LSB Spirals and the FIR-H_2 Correlation. For bright, massive spiral galaxies, there is a well-established correlation between far-infrared (FIR) luminosity and H_2 mass (or CO luminosity; e.g., Young & Scoville 1991). This correlation is assumed to arise from heating of dust grains embedded in giant molecular clouds (GMCs) by hot young stars. There are a number of reasons why this correlation might break down for LSB spirals; for example, if molecular gas in LSB spirals resides primarily outside GMCs, if their stellar mass function is biased toward low-mass stars (Lee et al. 2004), or if the appropriate CO-to-H_2 conversion factor for these galaxies is very different from what we have assumed.

Fig. 2 shows a plot of the nuclear H_2 masses (or 3σ upper limits) for our CO survey galaxies, versus the FIR luminosity derived from *IRAS* data. Also plotted is a sample of extreme late-type spirals recently surveyed in CO by Boeker et al. (2003; hereafter B03). The B03 sample comprises the same range of redshifts and Hubble types as our LSB spiral CO surveys, but covers a wide range in surface brightness, including two LSB spirals [$\mu_I(0) \geq 21.4$ mag arcsec^{-2}], 15 intermediate surface brightness (ISB) spirals [$18.7 \leq \mu_I(0) < 21.4$ mag

arcsec^{-2}], and 25 high surface brightness (HSB) spirals. Also overplotted as a solid line on Fig. 2 is the H_2-FIR relation derived by B03 for a sample of brighter, more massive galaxies.

Fig. 2 reveals that the CO-detected LSB spirals delineate a remarkably tight extension of the H_2-FIR defined by brighter galaxies. Only a handful of the LSB/ISB galaxies undetected in CO show evidence of possible deviation from this correlation. Our findings suggest that as in brighter galaxies, the CO detected in LSB spirals is associated with dense molecular clouds and sights of massive star formation rather than a more diffuse molecular medium.

A Link between Disk Rotational Velocity and the Detectability of CO in Low-Mass Galaxies. Fig. 3 plots the nuclear H_2 mass versus the inclination-corrected total H I linewidth ($W_{20}/\sin i$) for the same samples shown in Fig. 2. W_{20} is related to the maximum rotational velocity of disk galaxies as $V_{\rm rot} \approx 0.5(W_{20} - 20)/(2\sin i)$ (see M05).

We see that for larger rotational velocities ($W_{20}/\sin i > 250$ km s^{-1}), the quantities plotted on Fig. 3 shows a nearly flat correlation. However, for galaxies with $W_{20}/\sin i < 200$ km s^{-1} (corresponding to $V_{\rm rot} \lesssim$90 km s^{-1}), the inferred nuclear H_2 mass (i.e., the CO detectability) begins to drop significantly, and no ISB or LSB spirals below this limit have so far been detected in CO. As discussed by M05, it appears that neither decreasing mean H I surface density, nor decreasing metallicity among the lower mass galaxies can fully account for this trend. Fig. 3 therefore points toward a decreasing concentration of molecular gas in the inner regions of galaxies with decreasing rotational velocity. This trend seems to depend only weakly on optical central surface brightness in the sense that both LSB and ISB galaxies show similar declines in CO detectability with $V_{\rm rot}$, although a few HSB systems with low $V_{\rm rot}$ do have CO detections.

It is interesting to note that the characteristic velocity, $V_{\rm rot} \approx$90 km s^{-1}, below which we see a decline in the detectability of CO among late-type spirals is similar to the velocity characterizing a slope change in the optical Tully-Fisher relation for H I-rich, extreme late-type disks found by Matthews et al. (1998) ($V_{\rm rot} \sim$90 km s^{-1}), the characteristic rotational velocity below which star formation appears to have been suppressed at high redshift ($V_{\rm rot} \sim$100 km s^{-1}; Jimenez et al. 2005), and the rotational velocity below which galaxy dust lanes are seen to disappear ($V_{\rm rot} \sim$120 km s^{-1}; Dalcanton et al. 2004). *All of these results are consistent with fundamental changes in some key parameter(s) governing the ISM conditions and the regulation of star formation in low-mass galaxies*. Possible causes could include: a decreasing fraction the disk unstable to GMC formation (e.g., Li et al. 2005), a change in the characteristic velocity for turbulence (Dalcanton et al. 2004), an increasing fraction of the disk below the critical pressure needed for the existence of a cold ISM

phase (Elmegreen & Parravano 1994), the increasing dominance of gas relative to stars in the underlying disk potential, and/or decreasing effects of rotational shear (e.g., Martin & Kennicutt 2001). We are presently undertaking additional multiwavelength observations of our CO survey sample to better constrain the importance of these various effects.

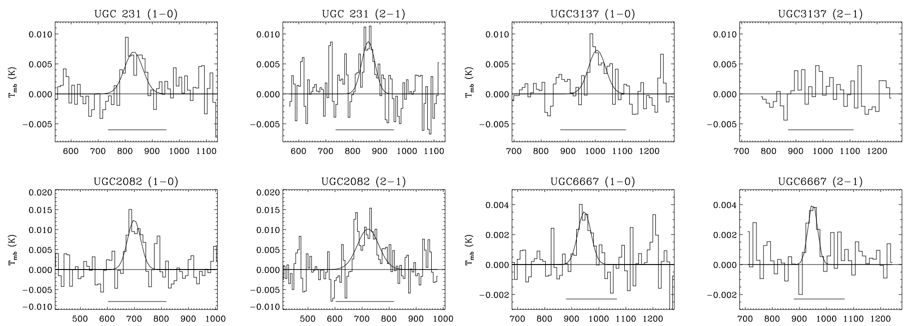

Figure 1. CO(1-0) and (2-1) spectra of four late-type, LSB spiral galaxies detected by M05.

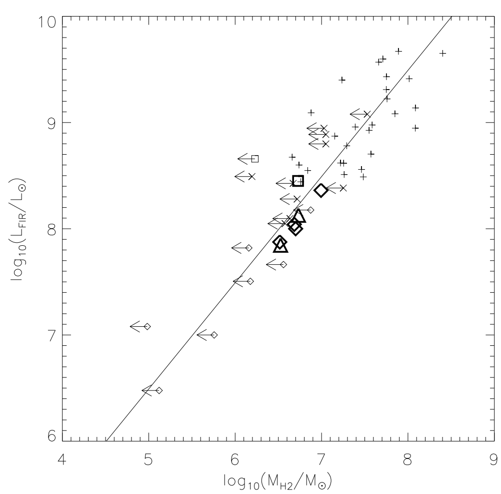

Figure 2. Log of the far-infrared luminosity versus log of the nuclear H_2 mass for extreme late-type spiral galaxies. M_{H_2} was derived from a single measurement with a telescope beam subtending $\sim$0.2-2 kpc toward each galaxy's center. Open symbols are LSB spirals taken from three different sources: triangles (Matthews & Gao 2001); diamonds (M05); squares (B03). '+' symbols are HSB spirals and 'X' symbols are ISB spirals, both taken from B03.

References

Boeker, T., Lisenfeld, U., & Schinnerer, E. 2003, A&A, 406, 87 (B03)
Bothun, G., Impey, C., & McGaugh, S. 1997, PASP, 109, 745
Dalcanton, J. J., Yoachim, P., & Bernstein, R. A. 2004, ApJ, 608, 189

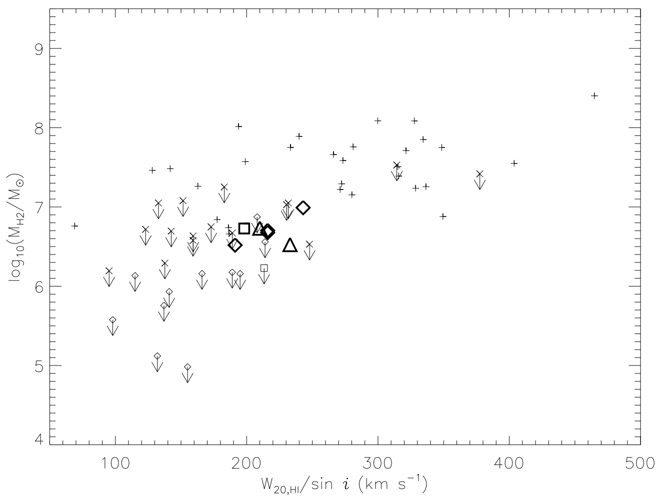

Figure 3. Log of the nuclear molecular hydrogen mass versus inclination-corrected total H I linewidth for extreme late-type spirals. Symbols are as in Figure 2.

de Blok, W. J. G., McGaugh, S. S., & van der Hulst, J. M. 1996, MNRAS, 283, 18

de Blok, W. J. G. & van der Hulst, J. M. 1998, A&A, 336,49

Elmegreen, B. G. & Parravano, A. 1994, ApJ, 435, L121

Gallagher, J. S., III & Matthews, L. D. 2002, in Modes of Star Formation and the Origin of Field Populations, ASP Conf. Series, Vol. 285, ed. E. K. Grebel and W. Brandner (ASP: San Francisco), 303

Jimenez, R., Panter, B., Heavens, A. F., & Verde, L. 2005, MNRAS, 356, 495

Lee, H.-c., Gibson, B. K., Flynn, C., Kawata, D., & Beasley, M. A. 2004, MNRAS, 353, 113

Li, X., Mac Low, M.-M., & Klessen, R. S. 2005, ApJ, 620, L19

Martin, C. L. & Kennicutt, R. C. Jr. 2001, ApJ, 555, 301

Matthews, L. D., Gallagher, J. S., & van Driel, W. 1998, AJ, 116, 2196

Matthews, L. D. & Gao, Y. 2001, ApJ, 549, L191

Matthews, L. D., Gao, Y., Uson, J. M., & Combes, F. 2005, AJ, 129, 1849 (M05)

Mihos, J. C., Spaans, M., & McGaugh, S. S. 1999, ApJ, 515, 89

Minchin, R. F., et al. 2004, MNRAS, 355, 1303

O'Neil, K., Hofner, P., & Schinnerer, E. 2000, ApJ, 545, L99

O'Neil, K. & Schinnerer, E. 2004, ApJ, 615, L109

O'Neil, K., Schinnerer, E., & Hofner, P. 2003, ApJ, 588, 230

Schombert, J. M., Bothun, G. D., Impey, C. D., & Mundy, L. G. 1990, AJ, 100, 1523

Schinnerer, E. & Scoville, N. 2002, ApJ, 577, L103

van den Hoek, L. B., de Blok, W. J. G., van der Hulst, J. M., & de Jong, T. 2000, A&A, 357, 397

van der Hulst, J. M., Skillman, E. D., Smith, T. R., Bothun, G. D., McGaugh, S. S., & de Blok, W. J. G. 1993, AJ, 106, 548

Young, J. S. & Scoville, N. Z. 1991, ARA&A, 29, 581